High-energy WW scattering at the LHC

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based on A. F. & J. Gainer, arXiv:1212.3598

1. **Vector-boson scattering and EWSB**
2. **Matrix Element Method**
3. WW **scattering and MEM**
4. **Conclusions**

Vector-boson scattering and EWSB

- LHC Higgs data consistent with SM Higgs
- Complementary viewpoint from high-energy VV scattering
  - Test HVV couplings
  - Study unitarity restoration in $W_L W_L \to W_L W_L$

Possible new physics effects:

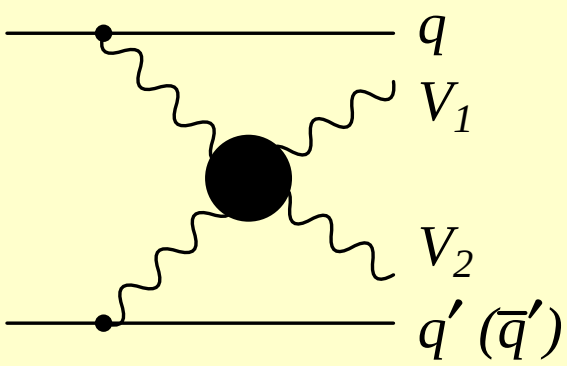
- Extended Higgs sectors (2 Higgs doublets, SUSY, etc.)
- Composite Higgs with energy-dependent form factors
- Higgs with non-perturbative self-coupling
- Additional (broad) resonances
- ...

Some models disfavored by electroweak precision and LHC data

$\to$ Independent check through VV scattering desirable
$VV = W^+W^+,\ W^+W^-,\ W^\pm Z,\ ZZ$

Existing work

Production at hadron colliders:



1. Apply smart cuts on vector-boson fusion (VBF) topology:
   $\longrightarrow$ two jets with large rapidity gap
2. Count events or analyze m_{VV}

Problem: typical event rate $\sim$ 0.1–0.5 fb at $\sqrt{s} = 14$ TeV

Duncan, Kane, Repko '86
Dicus, Vega '86
Kleiss, Stirling '88
Barger, Cheung, Han, Phillips '90
Baur, Glover '90
Dicus, Gunion, Vega '91
Dicus, Gunion, Orr, Vega '92
Bagger et al. '94,'95
Iordanidis, Zeppenfeld '98
Butterworth, Cox, Forshaw '02
Alboteanu, Kilian, Reuter '08
Englert, Jäger, Worek, Zeppenfeld '09
Ballestrero, Bevilacqua, Maina '09
ATLAS '09
Ballestrero, Franzosi, Maina '11
Doroba et al. '12

and others...

Matrix Element Method

Matrix Element Method (MEM):

Kondo '88,'91
Dalitz, Goldstein '92
DØ collaboration '99,'04

Likelihood that measured event, $\mathbf{p}_i^{\text{vis}}$, agrees with theoretical matrix element M_α:

$$\mathcal{P}(\mathbf{p}_i^{\text{vis}}|\alpha) = \frac{1}{\sigma_\alpha} \int dx_1 dx_2 \, \frac{f_1(x_1) f_2(x_2)}{2 s x_1 x_2} \times \left[\prod_{i \in \text{final}} \int \frac{d^3 p_i}{(2\pi)^3 2 E_i} \right] |M_\alpha(p_i)|^2 \prod_{i \in \text{vis}} \delta(\mathbf{p}_i - \mathbf{p}_i^{\text{vis}})$$

For sample of N events:

$$\chi^2 = -2 \ln(\mathcal{L}) = -2 \sum_{n=1}^{N} \ln \mathcal{P}(\mathbf{p}_{n,i}^{\text{vis}}|\alpha)$$

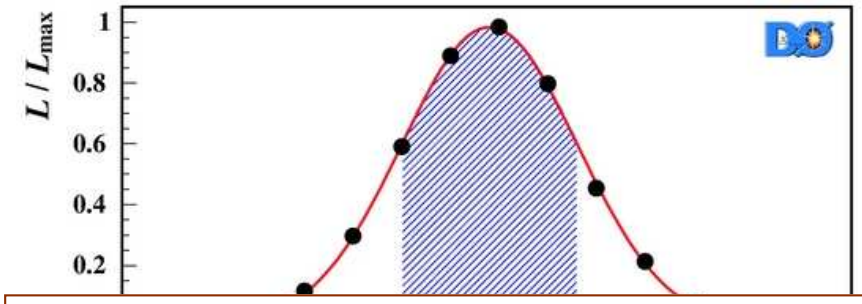
(+) Uses complete event information
(+) Effective for small event samples
(+) Works well also with invisible final-state objects

Applications of MEM

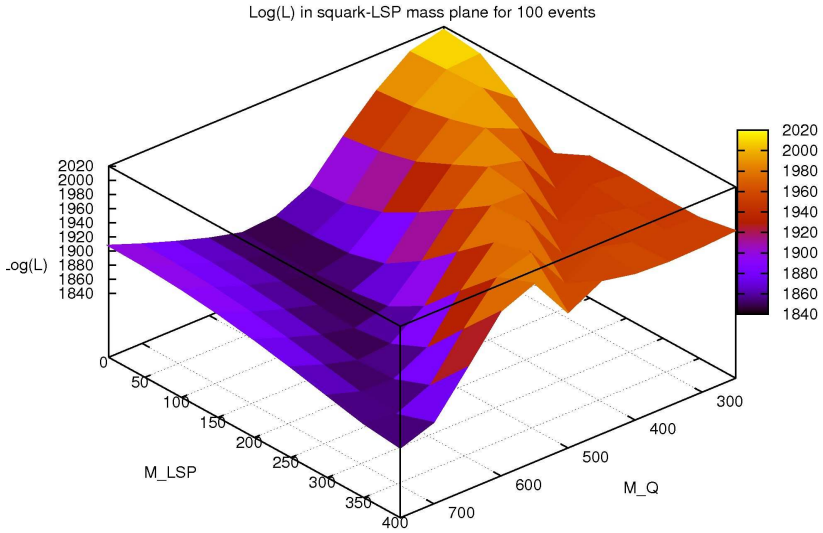
Top physics:

DØ '99,'04,'08,... CDF '06,'08,...

Fiedler et al. '10



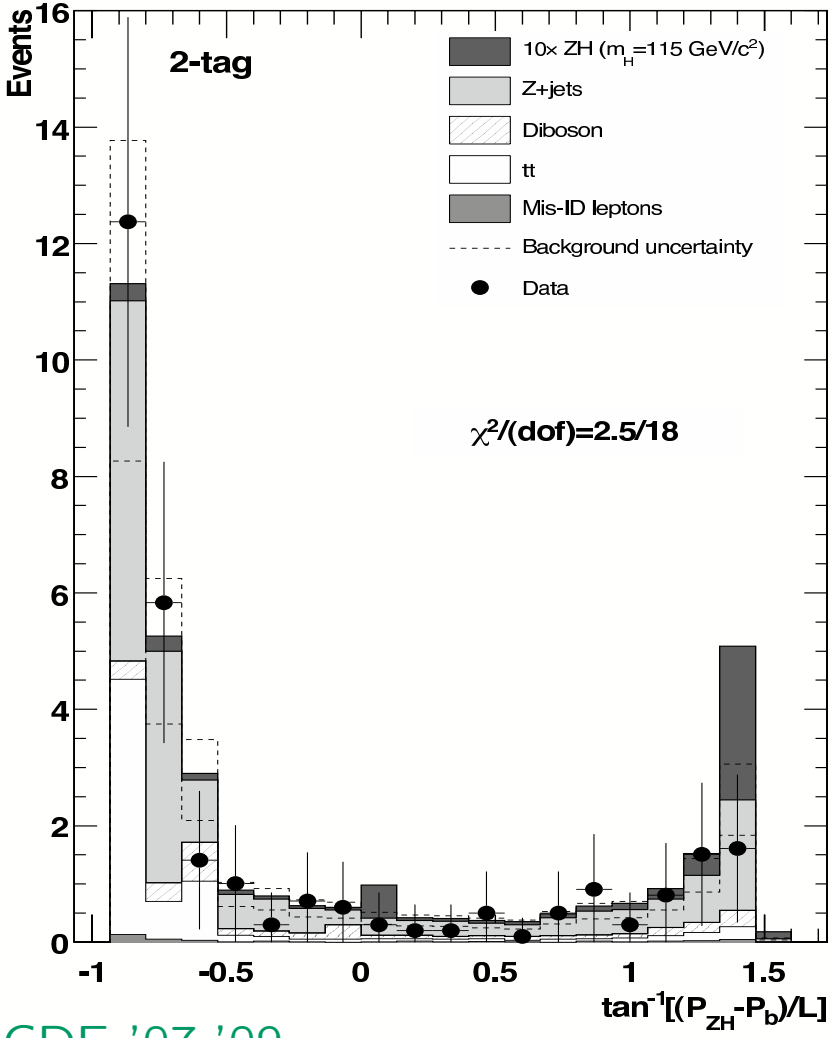
New physics:



Alwall, Freitas, Mattelaer '09

Chen, Freitas '10

Higgs searches:



CDF '07,'09

Therhaag '09

Gainer, Kumar, Low, Vega-Morales '11

WW scattering and MEM

Consider process: $pp \to jjW^+W^+ \to jj\ell^+\ell'^+\nu_\ell\nu_{\ell'}$ $\quad (\ell^{(\prime)} = e, \mu)$

(−) Relatively low event rate

(−) Final state cannot be reconstructed kinematically

(+) Clean final state (no jet ambiguity)

(+) Low background

Main backgrounds:

- Intrinsic $pp \to jjW^+W^+ \to jj\ell^+\ell'^+\nu_\ell\nu_{\ell'}$
  (contributions without $W_L^+W_L^+$ scattering)
- $pp \to t\bar{t} \to jj\ell^+\ell'^-\nu_\ell\bar{\nu}_{\ell'}$ Doboda et al. '12
  (due to wrong charge identification for $\mathcal{O}(1\%)$ of hard lepton tracks)

Implementation of MEM for WW scattering

Partonic process: $q\bar{q} \to q'\bar{q}'W^+W^+ \to q'\bar{q}'\ell^+\ell'^+\nu_\ell\nu_{\ell'}$ $(q, q' = u, d, s, c)$

- Analysis at parton-level (jet smearing functions are straightforward but computing intensive) DØ '04, Fiedler et al. '10
- Private code for likelihood weights and cross-section normalization
- MADGRAPH/MADEVENT/MADWEIGHT for cross-checks
- Simulation of "experimental" events with MADEVENT / ($m_h = 125$ GeV)

Preselection cuts:

$p_{\mathrm{T},\ell} > 20$ GeV	$p_{\mathrm{T,j}} > 30$ GeV	$\lvert\eta_\ell\rvert < 2.5$	$\lvert\eta_j\rvert < 5$	(acceptance)
$\Delta R_{jj,\ell j,\ell\ell} > 0.4$				(isolation)
$\lvert\eta_{j_1} - \eta_{j_2}\rvert > 4$	$\lvert\eta_j\rvert > 1$	$m_{j_1 j_2} > 100$ GeV		(VBF cuts)
$m_{\ell j} > 190$ GeV				($t\bar{t}$ bkgd.)

SM cross-section ($\sqrt{s} = 14$ TeV): $\sigma = 0.59$ fb

$\to$ 100 events with $\mathcal{L} \sim 170$ fb^{-1}

Strongly Interaction Light Higgs (SILH)

Class of models with strong dynamics at $\Lambda \sim 4\pi f > 1$ TeV
and light composite Higgs boson (here $m_H = 125$ GeV)

Guidice, Grojean, Pomarol, Ratazzi '07

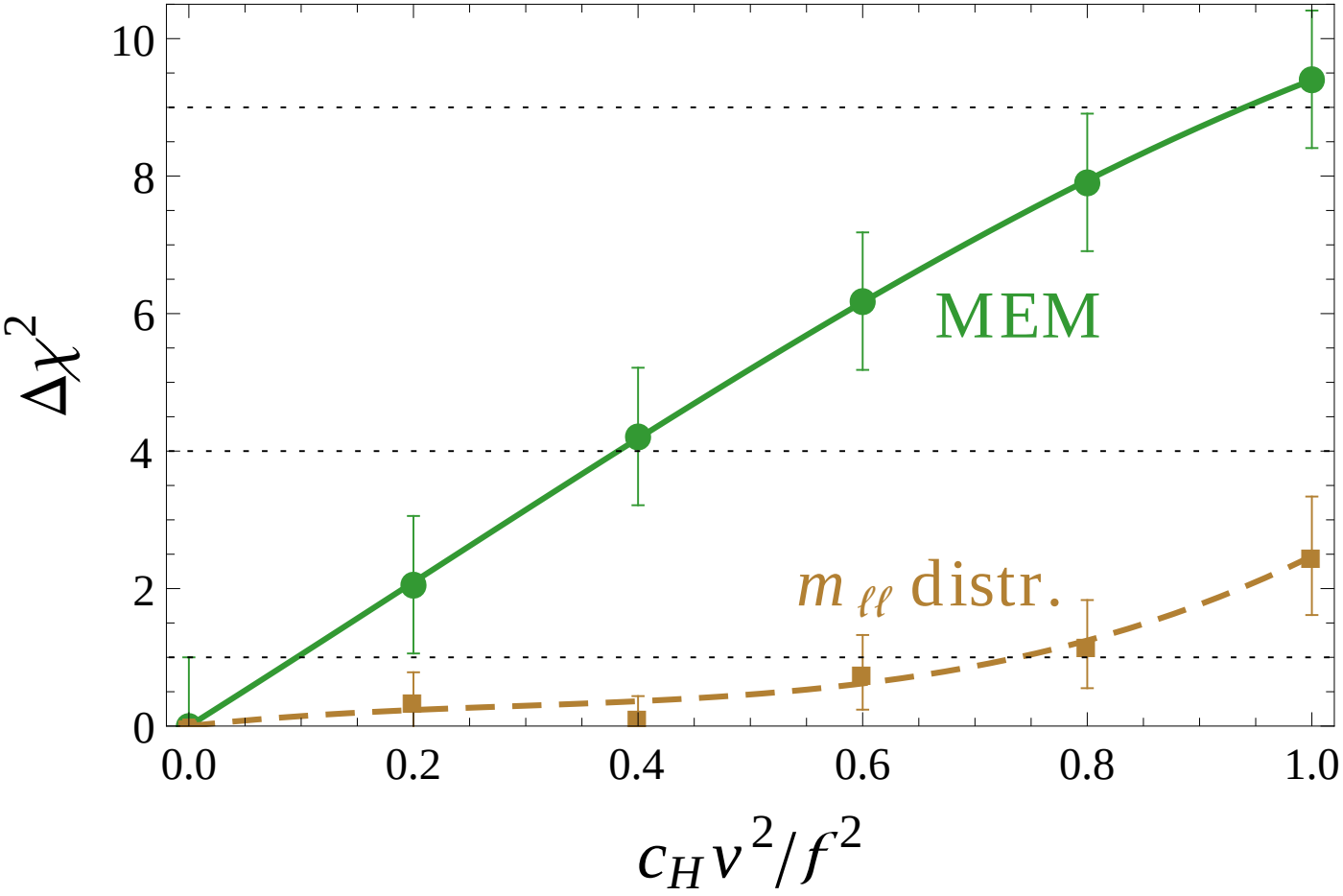
- Higgs couplings to SM particles reduced by $1/\sqrt{1 - c\,v^2/f^2}$, $c \sim \mathcal{O}(1)$
- Full unitarization for $M_{WW} \to \infty$ by heavy resonances ($m \sim$ few $\times f$)
  $\longrightarrow$ May be beyond reach of LHC

Results: SILH

MEM: 100 events at $\sqrt{s} = 14$ TeV for $pp \to jjW^+W^+ \to jj\ell^+\ell'^+\nu_\ell\nu_{\ell'}$

Traditional analysis: $m_{\ell\ell}$ distribution, 2 bins for $m_{\ell\ell} \in [0, 1000]$ GeV,

(results compatible with Ballestrero, Franzosi, Maina '11)



Two Higgs Doublet Model (THDM)

Higgs-like particle with $m = 125$ GeV has been observed

$\longrightarrow$ Could be one of two CP-even Higgs states h^0 and H^0 ($m_{h^0} = 125$ GeV)

$\longrightarrow$ Both needed for complete unitarization

Mixing angles:

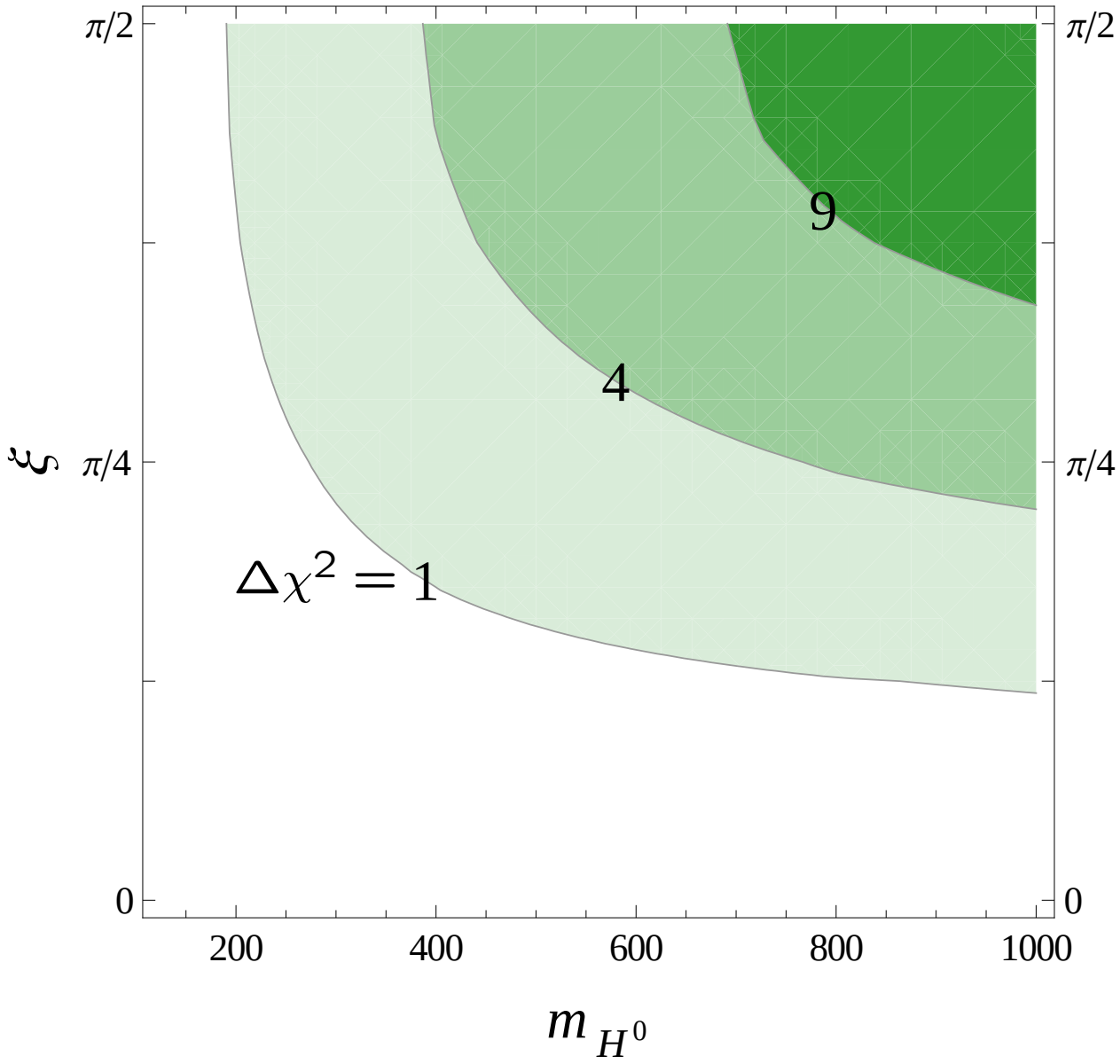
$$h^0 = \cos\alpha\, H_1^0 - \sin\alpha\, H_2^0$$
$$H^0 = \sin\alpha\, H_1^0 + \cos\alpha\, H_2^0$$

$$\frac{g(h^0WW)_{\text{THDM}}}{g(HWW)_{\text{SM}}} = \cos(\beta-\alpha) \equiv \cos\xi$$

$$\frac{g(H^0WW)_{\text{THDM}}}{g(HWW)_{\text{SM}}} = \sin(\beta-\alpha) \equiv \sin\xi$$

$$\tan\beta = \langle H_2^0\rangle / \langle H_1^0\rangle$$

Results: THDM



100 events

$\sqrt{s} = 14$ TeV

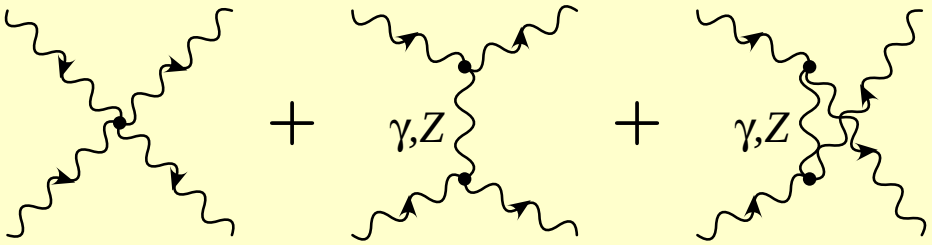
Conclusions

- High-energy VV scattering central for testing mechanism of EWSB
- MEM significantly improves sensitivity compared to traditional analysis methods
- Does not require resolution of a resonance
  $\longrightarrow$ Useful for "nightmare" scenarios with very broad resonances
- Systematic uncertainties:
  - Jet energy scale: can include as free parameter in fit DØ '04
  - QCD corr.: small (few %) for VBF Jäger, Oleari, Zeppenfeld '09
  - Quark/antiquark PDFs: can obtain from Drell-Yan

Backup slides

Vector-boson scattering and unitarity

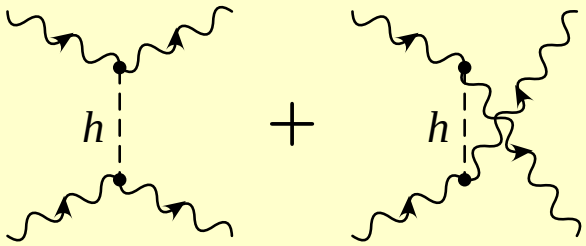
Example: $W_L^+ W_L^+ \to W_L^+ W_L^+$



$$\mathcal{M}_{\text{Gauge}} = \frac{t}{v^2} + \frac{u}{v^2}$$

$\to$ Grows linearly for $s \to \infty$

SM Higgs contribution:



$$\mathcal{M}_{\text{Higgs}} = -\frac{1}{v^2}\left(\frac{t^2}{t - m_H^2} + \frac{u^2}{u - m_H^2}\right)$$

$$\mathcal{M}_{\text{Sum}} = -\frac{m_H^2}{v^2}\left(\frac{t}{t - m_H^2} + \frac{u}{u - m_H^2}\right)$$

Results: SM

MEM: 100 events at $\sqrt{s} = 14$ TeV for $pp \to jjW^+W^+ \to jj\ell^+\ell'^+\nu_\ell\nu_{\ell'}$

Traditional analysis: $m_{\ell\ell}$ distribution, 2 bins for $m_{\ell\ell} \in [0, 1000]$ GeV, (same event sample)